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**ROBOTIC INSPECTION OF PROTOTYPE
TITANIUM DIFFUSION BOND FINAL CLOSURE
WELD - FINAL REPORT**

Report No. 89-247-K

R.J. Piercy, J.R. Antonacci and M.D.C. Moles
Nondestructive and Fracture Evaluation Section
Metallurgical Research Department

ABSTRACT

A commercial industrial robot has been used to ultrasonically inspect a prototype titanium diffusion bond both remotely and reliably. The robot's mapping stage is slow, though there are several possibilities for speeding it up. The robot's scanning shows that defects as small as 127 microns in diameter can be detected.

job	file	date	report no.
83-108-551	826.114	November 14, 1989	89-247-K



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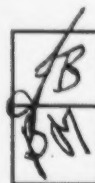
EXECUTIVE SUMMARY

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This report describes the ultrasonic inspection of a prototype titanium diffusion bond for a nuclear used fuel container. A commercial industrial robot is used for the delivery system, controlled by a personal computer. Initially, the robot maps the container, which may not be perfectly round. Then the robot scans the container for defects. The results show that a reliable robotic inspection can be performed remotely. The robotic inspection shows a similar sensitivity to laboratory inspections, with 127 micron tungsten wires being roughly the limit of detection. The main limitation of the current robotic system is its slow speed, though there are a number of possibilities for speeding it up. Specifically, multiple inspection systems, faster computer hardware, interpolating the mapping procedure, building a custom pipe scanner or developing faster inspection techniques could all raise the inspection rate to that required.



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TO: Mr. P.D. Stevens-Guille
Radioactive Materials Management Engineer
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**ROBOTIC INSPECTION OF PROTOTYPE
TITANIUM DIFFUSION BOND FINAL CLOSURE WELD
FINAL REPORT**

1.0 PURPOSE

To demonstrate that a nuclear used fuel container can be inspected remotely and reliably.

2.0 SUMMARY

This report describes the ultrasonic inspection of a prototype titanium diffusion bond for a nuclear used fuel container. The delivery diffusion mechanism is a commercial, industrial robot, and the system is controlled by a PC. The robot initially maps the container, which may not be perfectly round, then scans the container weld. Once the robotic system was debugged, the results showed that the container can be reliably and consistently inspected at a high level of sensitivity.

3.0 CONCLUSIONS

1. Reliable, remote, robotic inspection of a prototype titanium diffusion bond for a nuclear used fuel container has been demonstrated.
2. The inspection shows a similar sensitivity to laboratory inspections, with 127 micron tungsten wires being roughly the limit of detection.
3. The current robotic inspection system is slow, but expected technical advances, current modifications or alternative inspection techniques could improve speeds to the level required.

4.0 INTRODUCTION

1.1 Nuclear Fuel Waste Disposal Program

The current Canadian concept for disposal of used fuel from CANDU nuclear reactors is to isolate the fuel in corrosion-resistant containers, and to place the containers at a depth of 500 to 1000 meters in plutonic rock. As part of its Technical Assistance Program within the Nuclear Fuel Waste Management Program of Atomic Energy of Canada Limited, Ontario Hydro is performing Containment and Immobilization studies. Part of this program involves developing remote nondestructive evaluation (NDE) techniques for the final closure weld of the used fuel container.

Ultrasonic inspection, which can be performed remotely, has been selected as the most useful NDE technique for weld inspection, possibly supplemented by other techniques. The objective of the NDE inspection is to ensure the structural integrity of the weld, and that a necessary minimum corrosion barrier exists/1,2/. Since the container is the only absolute barrier, it is important to demonstrate that it can be reliably and remotely inspected.

1.2 Titanium Diffusion Bonds

One of the leading candidates for a waste disposal container involves a thin-walled, corrosion-resistant container made of 4.76 mm thick titanium plate (see Figure 1)/3/. Conventional fusion welding of titanium alloys presents problems due to weld contamination, and diffusion bonding has been investigated as a potential alternative. Diffusion bonding consists of pressing two sheets of metal together under conditions of time, temperature and pressure sufficient for diffusion to occur and give a metallurgical bond. The pressure, temperature and time conditions, and freedom from contamination at the interface, are important in producing a sound joint with no lack of bonding.

Previous work on the laboratory inspection of titanium diffusion bonds showed that normal beam pulse echo ultrasonics reliably detected the deliberately implanted defects/4,5/. In this technique, the transducer receives a signal reflected from defects or lack of bonding, as shown in Figure 2. In the laboratory, small specimens can be immersed in water for coupling, but this is far from an ideal solution for large nuclear used fuel containers. Contact coupling is not realistic because of the ridges left behind from the diffusion bonding process. A waterjet-coupled transducer offers the optimum solution, but mapping and tracking of the surface becomes considerably more critical than for contact methods.

Previous work on developing a remote system was based on using a commercial industrial robot, a Unimation PUMA 560, interfaced to an IBM-PC compatible Sperry microcomputer. The system both mapped the surface and then scanned it for defects/6/.

1.3 Objective

This report describes the final development of the robotic inspection system for a prototype titanium diffusion bond of a nuclear used fuel container final closure weld. The objective is to demonstrate that diffusion bonds can be reliably inspected for defects using a remote system. The advantages and limitations of the current system are discussed.

2.0 ROBOTIC INSPECTION SYSTEM

2.1 System Configuration

As mentioned, the inspection system is based on a commercial PUMA 560 robot interfaced to an IBM-PC compatible. The PC acts as the user interface to the system, collects and displays the ultrasonic scan data, and controls the tracking of the surface (see Figure 3). As shown in Figure 4, the PC's RS-232 serial port is connected to the PUMA robot controller terminal port for communication. The ultrasonic flaw detector generates an analog output proportional to the signal in the gate. Since the PC used a Labtender -5 to +5 volt A/D board, a voltage converter box was built so different flaw detectors with output voltages ranging from 1 to 10 volts could be used (see Figure 5).

A Harisonic 15 MHz unfocussed ultrasonic transducer and waterjet combination was connected to an extension of the robot's arm (see Figure 6). The transducer was typically driven by an EPOCH 2002 portable flaw detector for development work. For better scans, a Krautkramer KB6000 with an interface-controlled gate was used (see Figure 5). An immersion pump with recirculating water was used for ultrasonic coupling.

2.2 Previous Work on Robotic Inspection of Diffusion Bonds

Previously, Dowker and Moles developed the initial inspection procedure using the robot, the Sperry computer and the Epoch/6/. The inspection procedure was divided into two steps: mapping and scanning. The objectives of the mapping stage were

- (1) to measure the distance to the container to an accuracy of about 0.5 millimeters and
- (2) to determine the normal orientation to within ± 1 degree.

Such accuracies are needed for reliable scanning. The mapping coordinates were stored in the robot's PDP-11 computer. Several different procedures were investigated for mapping: airborne ultrasonics, waterjet coupling, and touch sensing/6/. Other techniques are possible, such as eddy current proximity sensors/7/, but these techniques are poor at estimating the normal orientation.

Not surprisingly, the (low frequency) airborne ultrasonics proved to be too inaccurate at estimating the normal. The touch sensing used a commercial JR3 sensor, with a triple point three-dimensional interpolation routine. However, this procedure also proved to be too inaccurate. In practice, only the waterjet ultrasonics technique appeared sufficiently sensitive to orientation to be acceptable.

The robotic inspection waterjet procedure did have problems. First, it was rather slow (discussed in Section 5 later). Second, the robot did not track as well as expected, and tripped out periodically. This work was primarily aimed at improving the tracking and reliability of the robot so that it could repeatedly and accurately scan the prototype diffusion bond.

3.0 MODIFICATIONS TO PREVIOUS PROCEDURE

3.1 Software Modifications

The software modifications were aimed at improving the reliability of the mapping procedure. The previous program/6/ would often stop due to an error condition. The program reliability was increased by fixing the signal threshold levels since the adjustable thresholds often caused errors when signal strength was low.

Reliability was improved further by moving fixed distances wherever possible. This minimizes the robot movements that continue until a certain signal condition develops, which had also led to errors when signal strength was low. Another source of program stoppages was the transfer from coarse to fine control when searching for the normal to the surface. Instead of using two passes, it was found that always using a fine and slow motion resulted in greater reliability.

Reliability was still further improved by using an average of five samples from the A/D board instead of a single sample. This eliminated many errors attributed to noise in the signal.

3.2 Hardware Modifications

A new bracket for attaching the waterjet sensor to the robot arm was built, which improved the accuracy with which the location of the used fuel container was mapped. The bracket allowed the robot arm to stay in a less cramped position while moving around the entire circumference of the container. It had been discovered that the robot arm positioning was significantly less accurate in cramped positions. The new bracket also corrected the angle at which the waterjet was held relative to the robot arm to ensure that the robot moved in the direction of the waterjet's jet when it was locating the container wall (see Figure 7).

3.3 Current Inspection Procedure

As before, the container was accurately set vertical, then mapped using 0.5, 1.0 and 2.0 millimetre circumferential steps. Mapping is performed by manually setting the robot's arm so that the front-wall signal is within the flaw detector's gate, and approximately 80% full screen height when maximized. The front wall signal was selected for maximizing since it was significantly higher amplitude than the backwall signals (see Figure 8). An unbonded region just above the bond was selected for mapping, since the diffusion bonding left a rough surface (see Figure 7).

Figure 9 shows a sample front wall signal in the flaw detector gate. This signal is maximized by the robot by twisting the wrist seven degrees left, then 14 degrees to the right. Then the robot returns to the maximum amplitude orientation (the normal), and moves the arm radially inward along this normal line until the frontwall signal moves out of the flaw detector gate. At this point, the analog output amplitude drops, which locates the position of the frontwall. The mapping points (orientation and location) were stored in the PDP-11 so repeated scans could be performed.

After mapping, the bond was scanned. The robot was set-up to scan over the bonded region, starting from the mapped line of points down a distance of typically 35 mm. Colour thresholds were preset by the operator, though no specified procedure was used to select them. C-scans (area-amplitude maps) were made of the bond at all three step sizes in pulse-echo (flaw detection) mode. Figure 10 shows the EPOCH CRT set-up for scanning, with a narrow gate centred on the region between the frontwall and backwall in the bonded area. Gain was increased for the scanning stage so lower amplitude reflections from the diffusion line defects could be detected. The robot scanned 360 degrees, then automatically stopped. The C-scans were stored on the PC using a predefined filename.

4.0 RESULTS

Figure 11 shows a sample 2.0 mm raster C-scan, Figure 12 a 1.0 mm raster C-scan, and Figure 13 a 0.5 mm raster C-scan. The defects are labelled in each case, and are taken from the nominal list of defects supplied by the manufacturer (see Table 1). With the exception of the 127 micron tungsten wires (not detected with the 0.5 mm raster scan, presumably due to higher threshold levels), the intentional defects are repeatedly detected in each C-scan. The slight variations from scan to scan are primarily due to variations in set-up of the flaw detector. In practice, such differences would be minimized by using a standard set-up procedure. These scans were performed using a Krautkramer KB6000 flaw detector, which minimizes differences in mapping due to its tracking gate.

The undulations in Figures 11 to 13 show that the bond was not made at a uniform distance from the top edge. The ragged edge at the top and bottom of the bonded region is due to the ultrasound beam being scattered by the ridges caused by the bonding process. Other small signals in the

bonded region can be attributed to scattering from ridges on the surface, indicating the gain is about as high as reasonably feasible with this ultrasonic system. Improved signal-to-noise would require more highly focussed transducers or signal processing, though a detection limit approaching 127 microns suggests that current sensitivity may be adequate.

Overall, the flaw detection scans show that the diffusion bond can be accurately and repeatably mapped, albeit at a slow rate.

5.0 DISCUSSION

5.1 Advantages and Disadvantages of the Robotic System

The results of this program show that it is technically feasible to remotely inspect a prototype titanium diffusion bond nuclear used fuel container final closure weld. The robotic technique can overcome the distortion inherent in the diffusion bonding process by mapping the surface to the required degree of accuracy. The results in Figures 11-13 show that the inspection technique is marginally capable of detecting a 127 micron diameter wire, which is a similar level of detection to the laboratory-type procedures/4,5/. In practice, improvements in ultrasonics expected over the next several years should produce capabilities better than those observed here.

Once the mapping procedure was debugged, the scanning produced very repeatable inspections. Small variations in C-scans were produced by changing gain level and threshold recording levels, but these problems could be surmounted either by establishing a standard inspection procedure, or by recording the amplitude level (not the threshold level) for future processing. Software for the second option is now becoming generally available. Use of an interface-controlled gate (standard on more expensive flaw detectors such as the KB6000) also improves C-scans by eliminating signals wandering into the gate.

The main disadvantage, at the current time, is the slow inspection speed. This applies especially to the mapping process, which takes a few hours for a 1 mm raster for this half-diameter prototype. The scanning itself is relatively quick. There are a number of alternatives for accelerating the inspection process (discussed below).

Another disadvantage of the current mapping procedure is the need to have the container accurately vertical. As the containers are expected to be well made and in a vertical position for inspection, this is not foreseen as a limiting factor.

5.2 Alternatives for Faster Inspections

The objective is to be able to remotely inspect a full-size container in about half an hour. The current system would take several hours, though there are many options for faster scans.

The first option would be to run multiple inspection systems. This is obviously an expensive and undesirable option.

The second alternative would be to speed up the present system. The robot itself can travel much faster than currently used for the inspection. A new 386-based PC and fast A/D card could process data much faster than the current set up. The current rate limiting step is communication between the robot's DPD-11 and the PC. Given that both pieces of equipment are at least five years old, and that computer technology is improving exponentially, it seems reasonable to expect logarithmic

improvements in communication speed here. This would likely bring the inspection speed to within the desired range. However, such improvements are probably outside the scope of this demonstration.

A third method of speeding up the present mapping by a factor of ten would be to map every tenth point and interpolate in between. This could be demonstrated with the current system.

The fourth alternative would be to build a custom pipe scanner which would be clamped onto the container for inspection. For a 2 mm raster, this requires about 35 metres of metal to be inspected (2,000 mm circumference or 1,000 passes at 35 mm per pass). For the 30 minute inspection time, this indicates travel speeds of 19.4 mm/sec, which is within current motor technology. Given advanced data handling techniques, it should be possible to both measure wall thickness and plot C-scans at this rate. The main problem with this approach is that the diffusion bonding does not leave a perfectly circular container to be inspected. The present prototype rings were roughly 1 mm out-of-round, and larger rings may be significantly worse. Under these conditions, the flaw detector may have trouble reliably normalizing on the bond line.

The fifth alternative is to develop inspection techniques which are faster than the current procedure. For example, a line-focussed transducer was tested, which could rapidly scan the ring in a single pass. While this transducer could detect the major defects, it has poorer signal-to-noise ratio and could miss some of the smaller defects. Another approach is to use Lamb (plate) waves to detect bonding or disbonding. This technique has been demonstrated using laser-generated waves, detected by electromagnetic acoustic transducers. The received signals were processed to give the cepstrum domain, and clear differences between the bonded and disbonded areas were visible/8/. This technique should be feasible in near real time.

6.0 ACKNOWLEDGEMENTS

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7. J.S. Schoenwald, M.S. Black, J.F. Martin, G.A. Arnold and T.A. Allison, "Application of Acoustics to Control Kinematic and Dynamic Behaviour in Robots", 1986 IEEE Ultrasonics Symposium, p. 539.
8. D.A. Hutchins (Queen's University, Kingston) - paper to be published at IEEE Conference, Montreal, Quebec, October 3-6, 1989.

TABLE 1**Listing of Embedded Defects. Supplied by BAL**

<u>Segment No.</u>	<u>Contents</u>
0 to 1	Standard Bond Parameters*
1 to 2	4% low on heat setting (60%)
2 to 3	2% low on heat setting (62%)
3 to 4	2% high on heat setting (66%)
4 to 5	4% high on heat setting (68%)
5 to 10	1 cycle power off*
	2 cycle power off*
	4 cycle power off*
	6 cycle power off*
	8 cycle power off*
10 to 11	.125 dia x .005 thick mica shim*
11 to 12	.25 dia x .005 thick mica shim*
12 to 13	.5 dia x .005 thick mica shim*
13 to 17	Room for 4 flat bottom holes*
17 to 19	3 glass fibre strands of approx. .010" dia*
19 to 20	3/8" wide strip of Titanium Oxide paste*
20 to 21	1/4" wide strip of Titanium Oxide paste*
21 to 23	3/8" wide strip of Zirconium Oxide paste*
22 to 23	1/4" wide strip of Zirconium Oxide paste*
23 to 27	Air oxide strips (tungsten arc generated)*
27 to 28	Room for flat bottom slit*
28 to 29	Locanite grease strip*
29 to 30	Tungsten wire (.005 dia)*
30 to 31	Tungsten wire twisted pair (.005 dia)*
31 to 32	Control strip of double sided tape*
32 to 38	Blank*
38 to 39	Close up
	65% for 1/2" before start
	66% for 1/4" before start
	67% for 3/4" past start

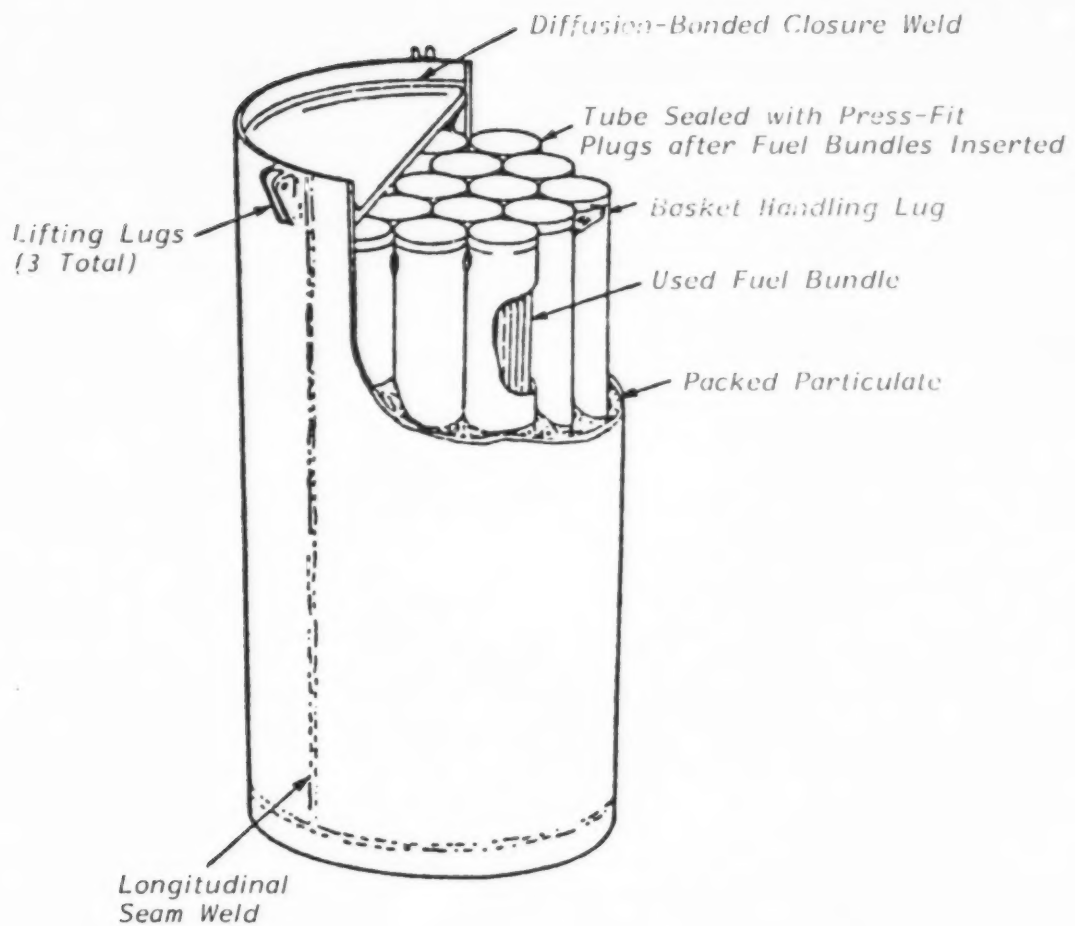


FIGURE 1
A CANDIDATE NUCLEAR FUEL WASTE DISPOSAL CONTAINER

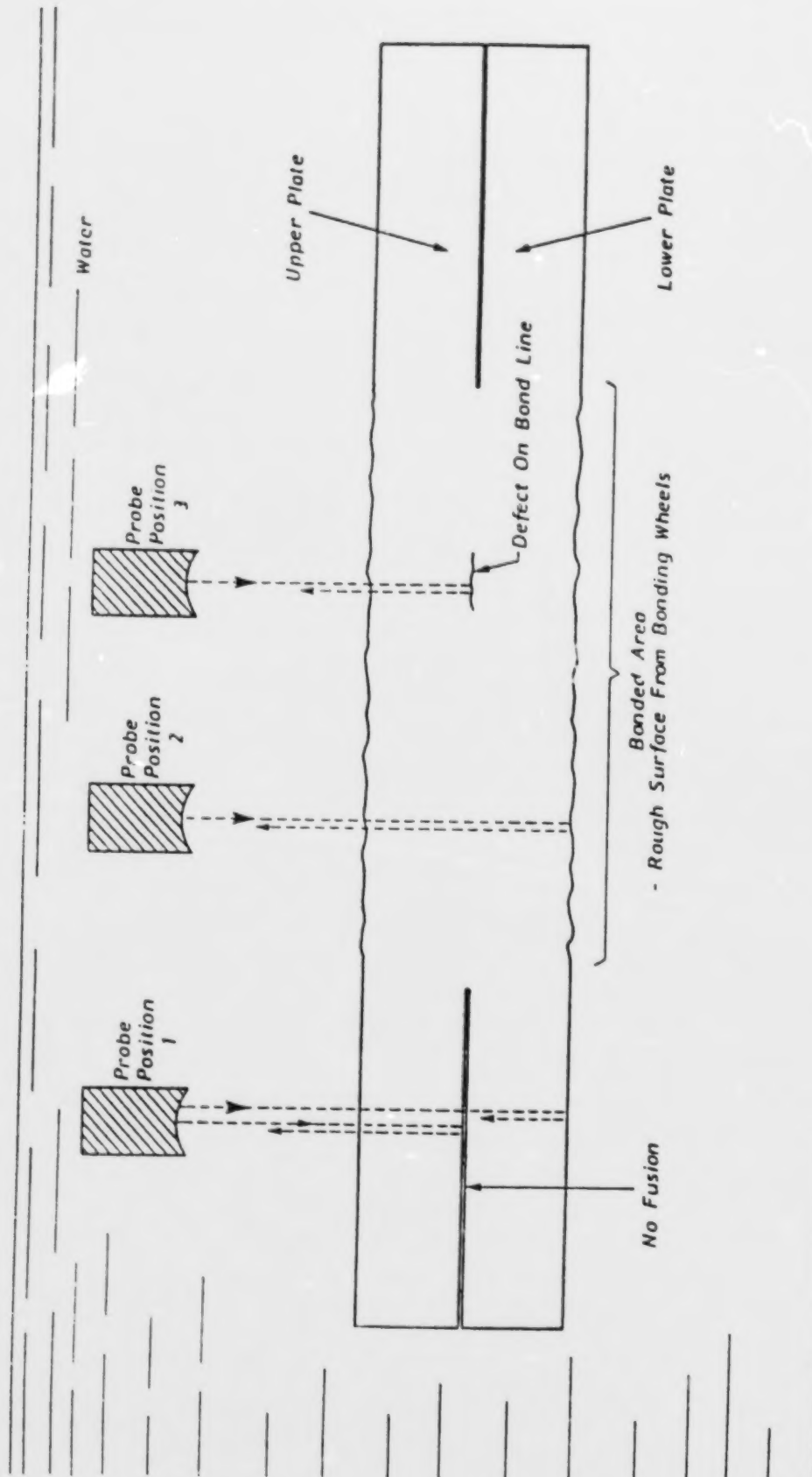


FIGURE 2
IMMERSION NORMAL BEAM FLPE INSPECTION OF DIFFUSION-BONDED PLATES

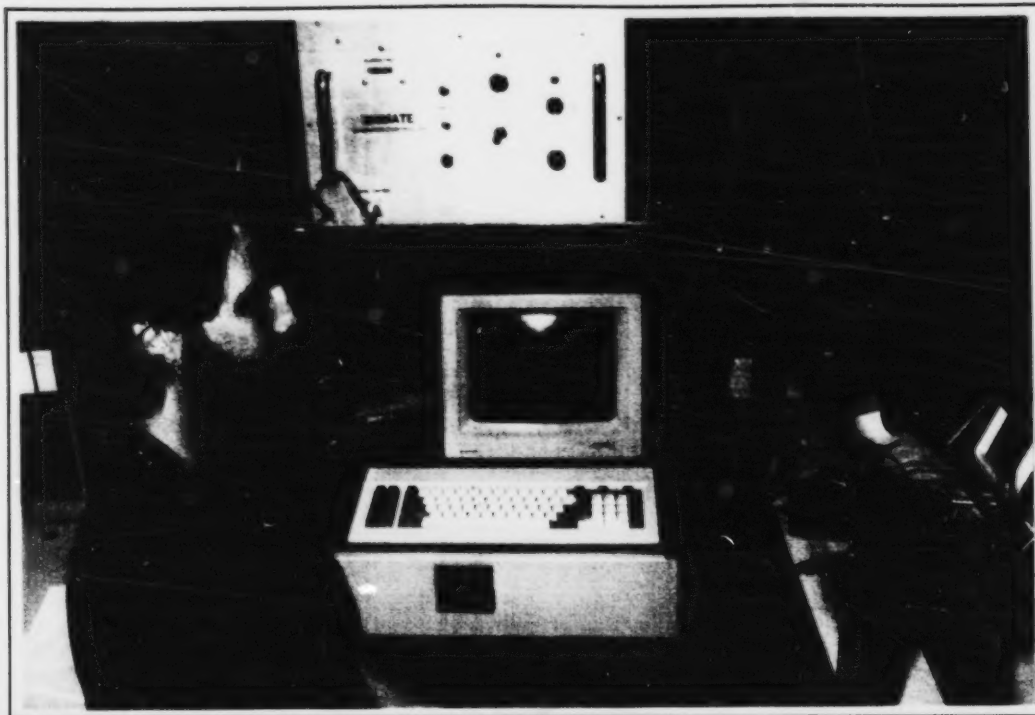


FIGURE 3

ROBOT CONTROL CONSOLE, PC AND
ULTRASONIC FLAW DETECTOR

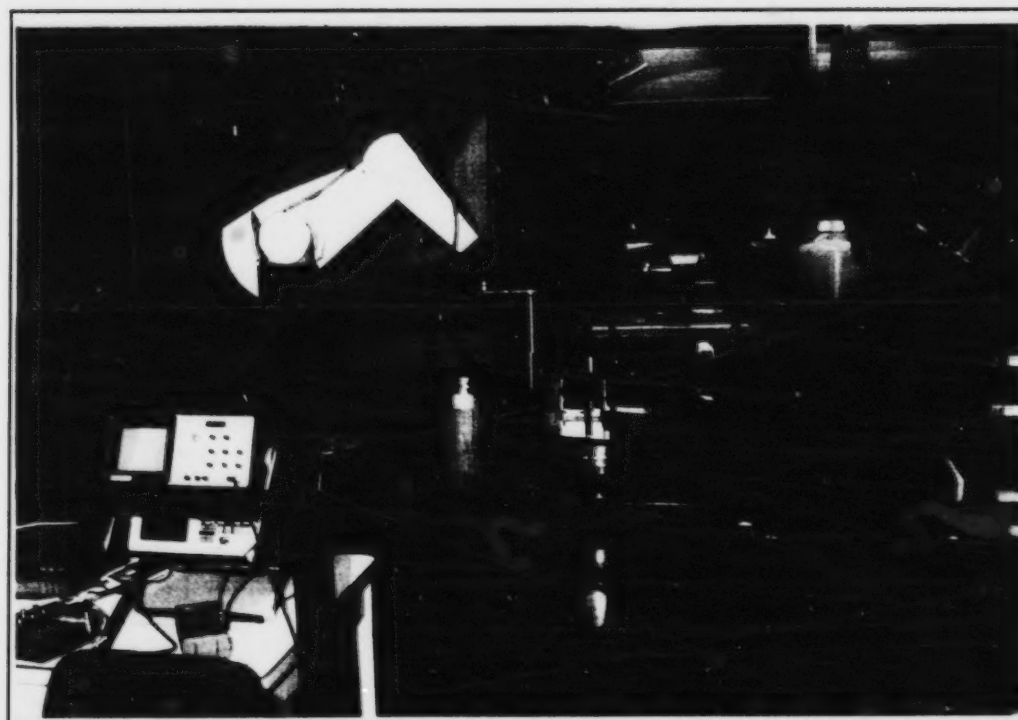


FIGURE 5

ROBOT SCANNING PROTOTYPE DIFFUSION BOND, WITH FLAW
DETECTORS AND VOLTAGE CONVERTER IN FOREGROUND

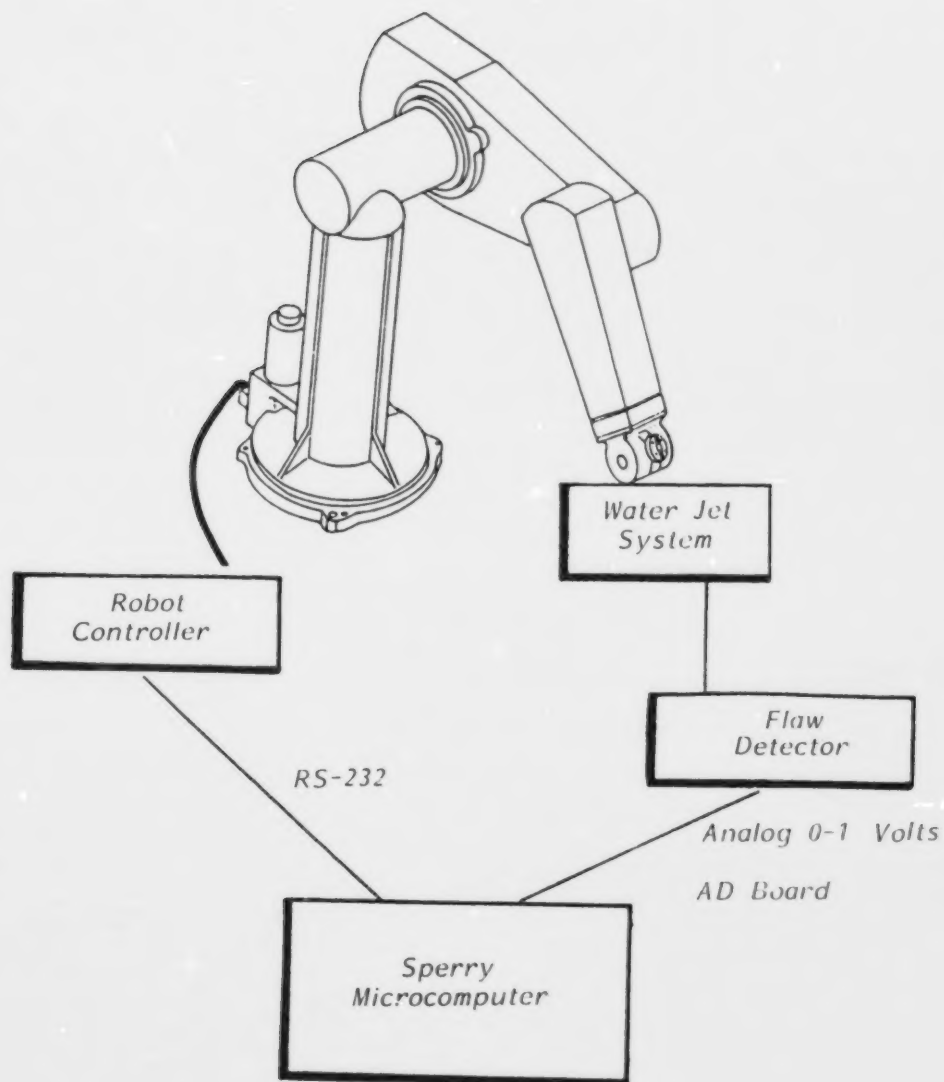


FIGURE 4
INSPECTION SYSTEM CONFIGURATION

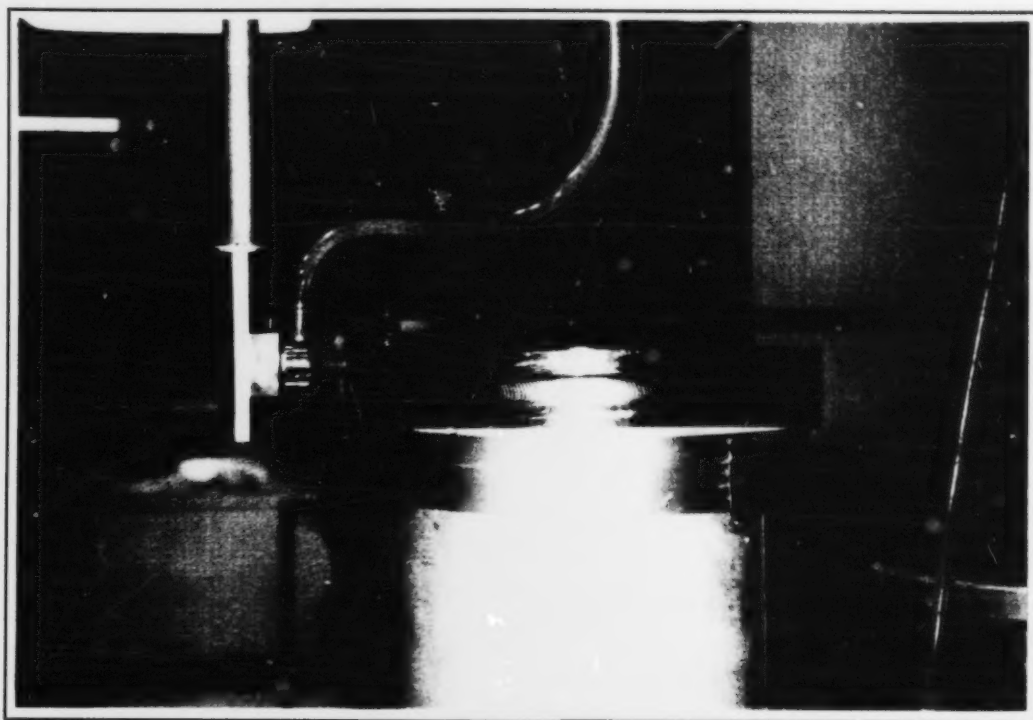


FIGURE 6

CLOSE-UP OF WATERJET INSPECTING DIFFUSION BOND RING

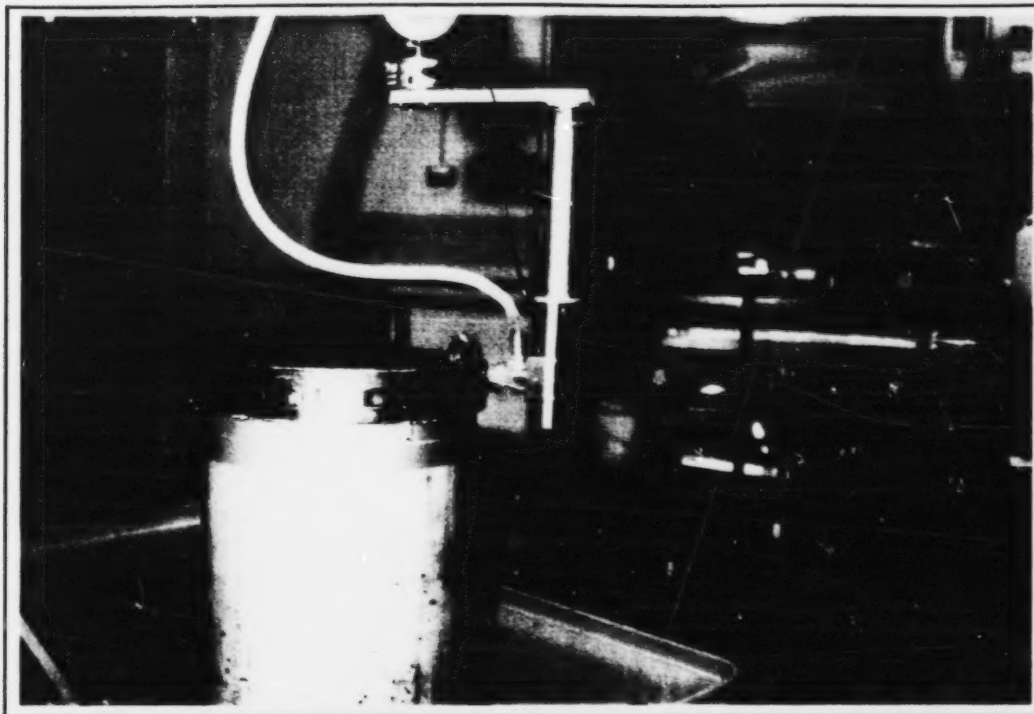


FIGURE 7

NEW BRACKET ON ROBOT, SHOWING MAPPING
ON SMOOTH SURFACE ABOVE DIFFUSION BOND

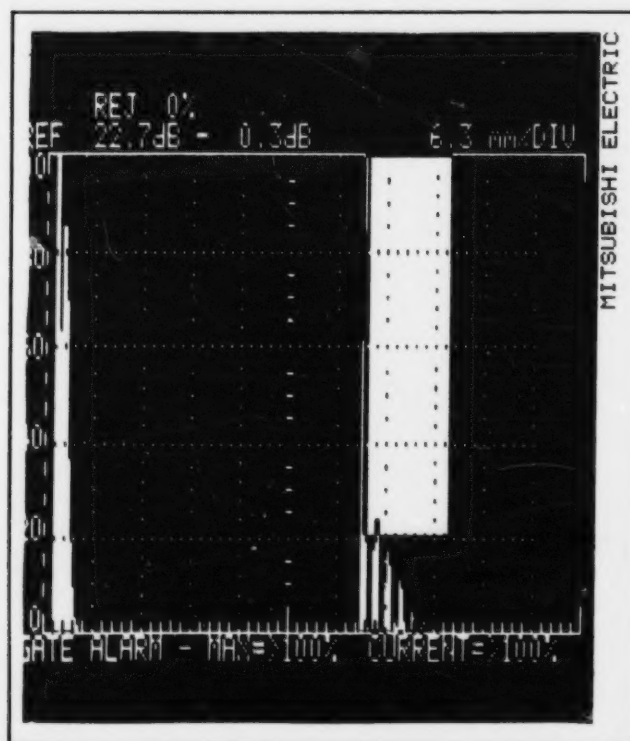


FIGURE 8

SAMPLE CRT PRINT-OUT FROM EPOCH,
SHOWING MULTIPLE SIGNALS WITH FRONTWALL
SIGNAL THE LARGEST

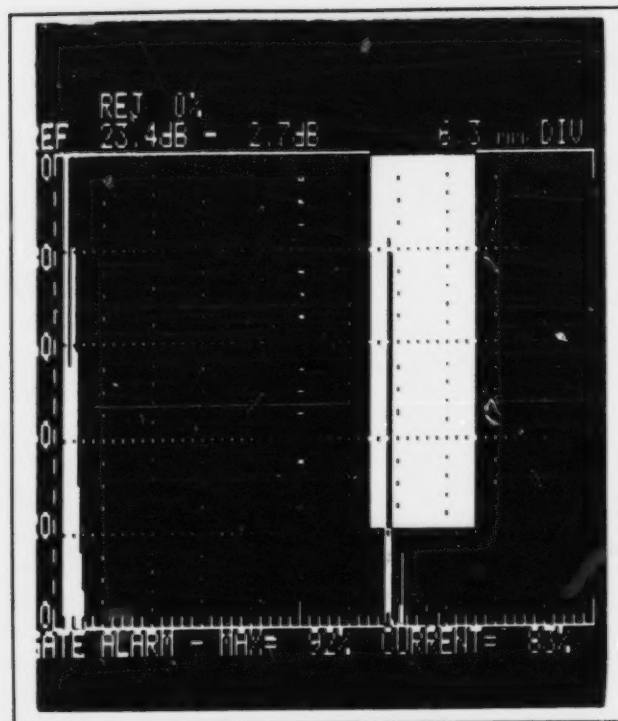


FIGURE 9

SAMPLE CRT PRINT-OUT FROM EPOCH 2002,
SHOWING FRONTWALL SIGNAL IN GATE

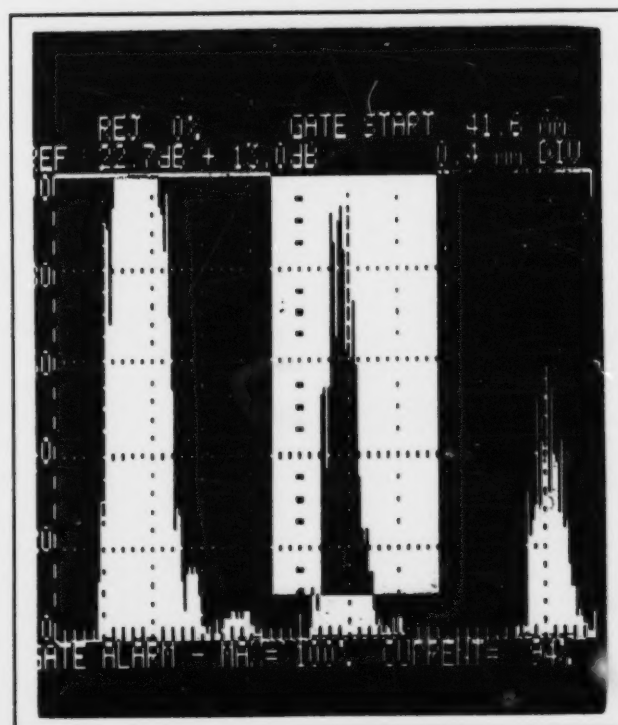


FIGURE 10

SAMPLE CRT PRINT-OUT FROM EPOCH FOR FLAW DETECTION
(Note Higher Gain)

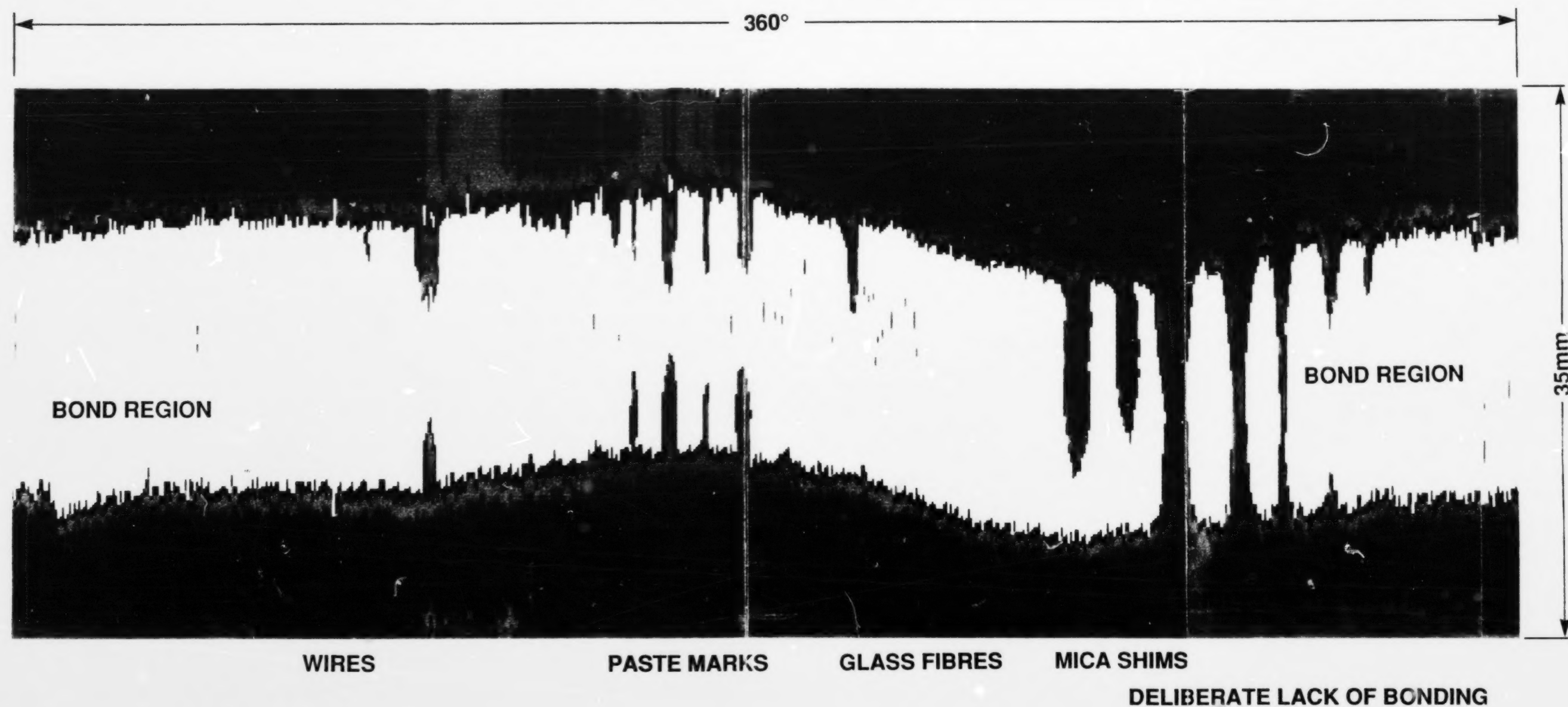


FIGURE 11
SAMPLE PRINT-OUT OF ROBOTIC SCAN
SHOWING EMBEDDED DEFECTS - 2mm RASTER

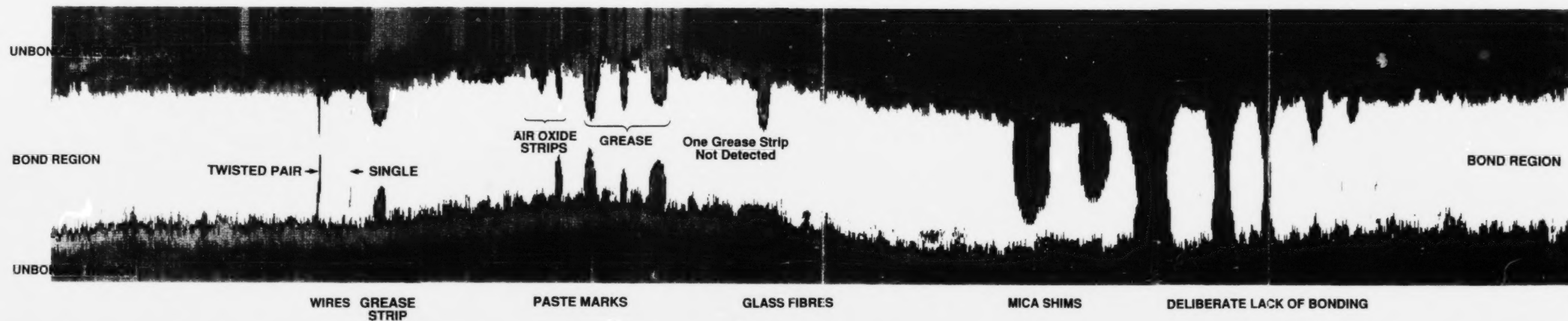


FIGURE 12
SAMPLE PRINT-OUT OF ROBOTIC SCAN
SHOWING EMBEDDED DEFECTS - 1.0mm RASTER

360° x 35mm

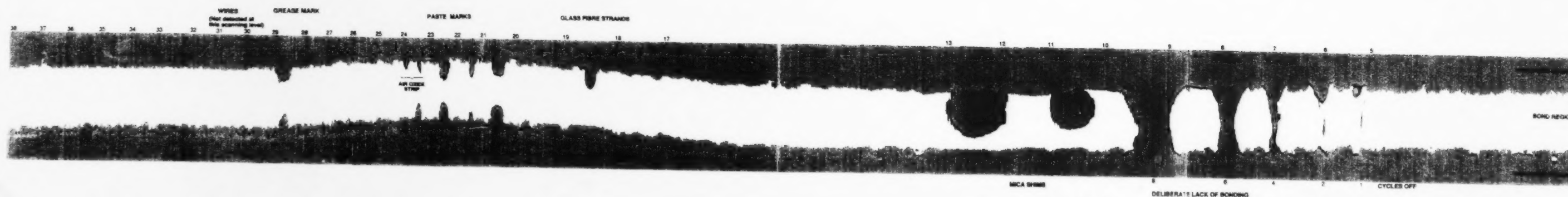


FIGURE 13
SAMPLE PRINT-OUT OF ACOUSTIC SCAN
SHOWING EMBEDDED DEFECTS - 0.5mm PASTER